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The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception

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Abstract

As the use of virtual and augmented reality applications becomes more common, the need to fully understand how observers perceive spatial relationships grows more critical. One of the key requirements in engineering a practical virtual or augmented reality system is accurately conveying depth and layout. This requirement has frequently been assessed by measuring judgments of egocentric depth. These assessments have shown that observers in virtual reality (VR) perceive virtual space as compressed relative to the real-world, resulting in systematic underestimations of egocentric depth. Previous work has indicated that similar effects may be present in augmented reality (AR) as well.

This paper reports an experiment that directly measured egocentric depth perception in both VR and AR conditions; it is believed to be the first experiment to directly compare these conditions in the same experimental framework. In addition to VR and AR, two control conditions were studied: viewing real-world objects, and viewing real-world objects through a head-mounted display. Finally, the presence and absence of motion parallax was crossed with all conditions. Like many previous studies, this one found that depth perception was underestimated in VR, although the magnitude of the effect was surprisingly low. The most interesting finding was that no underestimation was observed in AR.

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Keywords: depth perception, augmented reality, virtual reality, motion parallax

1 Introduction

Egocentric depth perception has been thoroughly investigated in virtual reality with many studies indicating that the locations of target objects relative to the observer are consistently underestimated [Loomis and Knapp 2003; Livingston et al. 2005; Swan II et al. 2007]. One explanation for this phenomenon is that, in purely virtual environments, observers are not presented with the full gamut of depth cues that are normally available when viewing a real-world scene. Hu et al. [2000] presented observers, in a near-field virtual environment, with varying numbers of depth cues and found a positive correlation between the number of available depth cues and accuracy when placing an object on a virtual surface, lending credence to this theory.

Although depth perception in virtual reality has been well studied, very little work has been done to determine if similar perceptual issues are present in augmented reality. One study conducted by Swan et al. [2007] indicates that similar underestimation effects exist in augmented reality, when viewing a scene through an optical see-through head-mounted display (HMD) from a fixed viewpoint. The experiment described in this paper attempts to replicate the findings reported by Swan et al. [2007], and determine if the addition of motion parallax as a depth cue will aid observers in more accurately perceiving the location of target objects. Another goal is to directly compare depth judgments in virtual and augmented reality. A related contribution of this paper is a novel calibration method that we developed to ensure proper registration of the virtual and real worlds.

2 Experimental Setup and Task

The experiment took place in a hallway where observers viewed a target object placed along the ground plane anywhere from 2 to 8 meters away. The target object was a white, wireframe pyramid measuring 23.5 cm in width and height. An NVIS nVisor ST optical see-through AR HMD was used for this experiment. One of the unique features of this HMD is that it can also serve as a VR HMD by attaching an occluding strip of black plastic with velcro. An InterSense IS-1200 VisTracker was attached to the HMD to provide 6 degree-of-freedom tracking of the observers' head movements. These were attached to a Dell Dimension XPS Gen 4 system. To allow the experimental observers to traverse the required distances, it was necessary to place the equipment on a rolling cart that was pushed behind the observers during the experimental tasks (see Figure 1). As discussed below, the experiment included control conditions to determine if this technique adversely affected the visually directed walking task.

One of the most common techniques used to measure an observer's judgment of egocentric depth is visually directed walking. In this task, observers view a target object for a period of time and then attempt to walk to the object's location without vision. Loomis and Knapp [2003] examined the findings of eight studies that used this technique to judge distances to real-world objects. They found that visually directed walking provided stable judgments of egocentric distance. In addition, they describe the theoretical arguments for why visually directed walking is a good cognitive measure of egocentric depth perception.

A small pilot study was conducted prior to collecting data for this experiment. Pilot observers appeared to be hesitant to walk with their eyes closed in an unfamiliar environment, but seemed to become comfortable after roughly five trials. For this reason, all observers were given five practice trials in a hallway adjacent to the experimental location prior to beginning the experiment. Pilot observers also indicated that light emanating from a corridor that intersected the experimental location disrupted their sense of position. It was important that the observers not be distracted during the visually directed walking task. To prevent interference during this ex-

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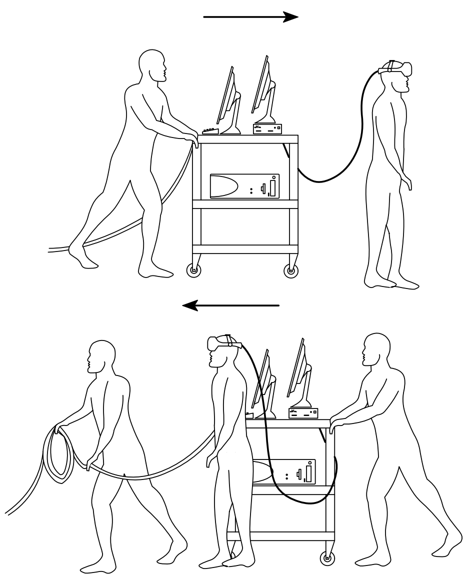

Figure 1: *Cart setup used for moving equipment behind observers both during (top) and after (bottom) visually directed walking tasks.*

periment, the corridor was occluded with a ceiling-suspended sheet that closely approximated the color and texture of the wallpaper in the experimental location. Also, to prevent interference from auditory cues, all observers wore earphones that played white noise throughout the duration of the experiment. Experimenters communicated instructions to the observers through a wireless microphone system that was also connected to the observers' earphones.

3 Variables and Design

Table 1 describes the experimental variables and design.

3.1 Independent Variables

Observers: We recruited 16 observers from a population of university students (undergraduate and graduate), faculty, and staff. 7 of the observers were male, 9 were female; they ranged in age from 19 to 37, with a mean age of 24.4. We screened the observers, via self-reporting, for color blindness and problems with depth perception. All observers volunteered, and were compensated $10 per hour for their time. Observers spent an average of 2.25 hours completing the experiment.

Viewing Conditions: As shown in Table 1, observers were presented with four viewing conditions: Real, Real+HMD, AR, and VR. In the Real condition, observers saw the real-world target object in the hallway, and did not look through the HMD. When they performed the visually directed walking task, the cart was not pushed behind them. We included this as a control condition, as it duplicates the setup of distance perception studies with real-world target objects [Loomis and Knapp 2003]. In the Real+HMD condition, observers saw the real-world target object in the hallway, but this time regarded the target object through the HMD. We included this as a second control condition, in order to determine if wearing the HMD and having the cart pushed behind the observer interfered with the visually directed walking task. In the VR condition, observers viewed a virtual target object in a completely virtual, photorealistic model of the hallway. This condition replicates many previous VR egocentric depth perception studies [Loomis and Knapp 2003]. Finally, in the AR condition, observers viewed a virtual target object in the real-world hallway. This was the only completely novel viewing condition studied.

Table 1: *Independent and Dependent Variables*

INDEPENDENT VARIABLES		
observer	16	(random variable)
viewing condition	4	Real Real+HMD AR VR
parallax condition	2	Still (absent) Motion (present)
distance	3	3, 5, 7 meters + 25% noise
repetition	2	1, 2
DEPENDENT VARIABLES		
judged distance	in meters	
normalized error	$\frac{\textit{judged distance}}{\textit{veridical distance}}$	

Parallax Condition: In the Still parallax condition observers were asked to hold their heads still while viewing the target object. This was intended to approximate the viewing conditions described by Swan et al. [2007], where the AR display was rigidly fixed in a stand. In the Motion parallax condition observers were asked to sway back-and-forth while viewing the target object, by shifting their weight from foot to foot. This was done to enable motion parallax as a depth cue.

Distance: For experimental trials, observers saw target objects placed at distances of 3, 5, and 7 meters. Because observers may notice the repetition in such a small set of distances, 25% of the distance judgments were noise trials. For these trials, distances were randomly chosen from 0.25-meter increments in the 2 to 8 meter range. The experimenters recorded the data from the noise trials using the same visually directed walking technique that was used for the experimental trials.

Repetition: Observers saw 2 repetitions of each combination of the other dependent variables.

3.2 Dependent Variables

As shown in Table 1, the primary dependent variable was *judged distance*, which was measured using the visually directed walking task. We also calculated *normalized error = judged distance / veridical distance*. A normalized error near 100% indicates an accurately judged distance; a normalized error $>$ 100% indicates overestimating the distance; and a normalized error $<$ 100% indicates underestimating the distance.

3.3 Experimental Design

We used a factorial nesting of independent variables in this within-subjects experimental design. As shown in Table 1, *viewing condition* varied the slowest; within each condition observers saw each *parallax condition*. The presentation order of *viewing conditions* was controlled by a 4×4 between-subjects Latin Square, while the presentation order of the *parallax conditions* was controlled by a 2×2 between-subjects Latin Square; when combined, these two Latin Squares resulted in a presentation order design that repeated modulo 8 observers. Within each *viewing condition* $\otimes$ *parallax condition* block, our control program generated a list of 3 (*distance*) $\times$ 2 (*repetition*) = 6 experimental distances, and then added 2 random noise distances. The program then randomly permuted the presentation order of the resulting 8 distances, with the restriction that the same distance could not be presented twice in a row. We

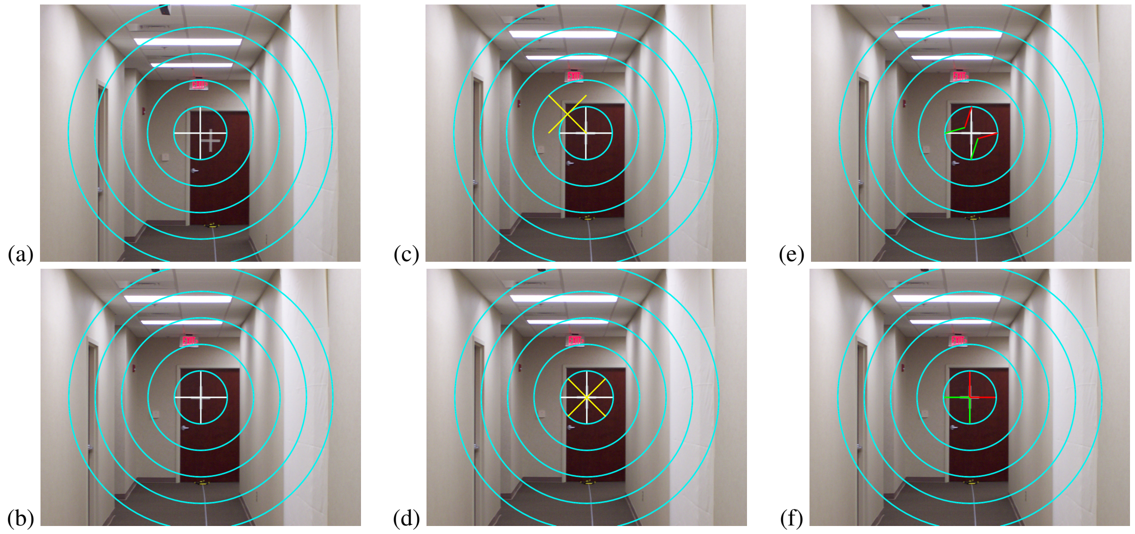

Figure 2: *Calibration procedure as seen by the observers: (a,b) initial virtual/real-world boresighting task, (c,d) translational correction, (e,f) rotational correction. See color plate.*

collected a total of 1024 data points (16 observers $\times$ 4 viewing conditions $\times$ 2 parallax conditions $\times$ (3 distances $\times$ 2 repetitions + 2 noise distances)); 768 of these data points were experimental trials, and 256 were noise trials.

Presentation order effects are a well-known issue for within-subjects designs. Between-subjects designs are immune to order effects, and the majority of VR depth perception experiments have used between-subjects designs. Furthermore, virtual versus real-world presentation order has been found to affect depth perception (e.g., [Ziemer et al. 2006; Plumert et al. 2005]). To mitigate presentation order effects in our within-subjects design, we used the following 4×4 Latin Square:

$$\begin{bmatrix} 1 & 2 & 3 & 4 \\ 2 & 4 & 1 & 3 \\ 3 & 1 & 4 & 2 \\ 4 & 3 & 2 & 1 \end{bmatrix}.$$

In addition to controlling presentation order (condition 1 is presented 1$^{\text{st}}$, 3$^{\text{rd}}$, 2$^{\text{nd}}$, and 4$^{\text{th}}$; likewise for conditions 2, 3, 4), this Latin Square controls the condition that *succeeds* each condition (condition 1 is succeeded by condition 2, condition 3, condition 4, and no condition; likewise for conditions 2, 3, 4), and it also controls the condition that *precedes* each condition (condition 1 is preceeded by no condition, condition 4, condition 3, and condition 2; likewise for conditions 2, 3, 4). These properties exist modulo 4 observers and are maintained modulo 8 observers when the 4×4 square is crossed with a 2×2 square. Therefore, asymmetric transfer effects (such as those described by Plumert et al. [2005]) are counterbalanced by this design.

4 Calibration

The calibration procedure used in this experiment consisted of three steps to correct for (1) optical alignment as well as (2) translational and (3) rotational errors reported by the head tracker.

Optical Alignment and Interpupillary Distance: The first step in the calibration procedure ensures that, for each eye, the observer's optical axis is aligned with the HMD's optical axis. To accomplish this, we implemented the calibration procedure presented by Rolland et al. [1995], who also demonstrate that without this alignment an optical system presents optically incorrect depth cues. The observers were presented with a series of concentric circles that were centered about the optical axis of the display elements (see Figure 2). The HMD has a knob on top of the head which raises and lowers the entire display frame relative to the observer's eyes. The observers were instructed to turn this knob until they could see an equal amount of the upper and lower portions of the outermost circle. The HMD also has knobs that independently shift the left and right display elements horizontally; observers were instructed to turn these knobs until an equal amount of the outermost circle could be seen on the left and right sides of each display. This procedure was performed monocularly for each eye. After these procedures, the optical axis of each of the observers' eyes was both horizontally and vertically aligned with the optical axis of each display element. In addition, each observer's interpupillary distance was measured with a small ruler. The graphics system used this distance when generating stereo imagery.

Translational Tracker Error: As part of developing the experimental apparatus, we carefully calibrated the 6 degree-of-freedom tracker for the hallway. However, because of differences in the way the HMD sits on the head, there are always noticeable translational and rotational errors, even if the display is removed and then replaced on the same observer's head. The goal of the second calibration step was to correct for tracker errors along the observers' x (horizontal) and y (vertical) axis. While similar errors also existed along the z (depth) axis, it was not necessary to correct for them, because the experimental task was always conducted at the same z location for each observer. For this calibration step, the observers were shown a virtual crosshair and a real-world cross placed at their eye height at the end of the hallway (Figure 2a). The observers were then asked to align the two crosshairs by moving their heads (Figure 2b). Once the observers had aligned the crosshairs, their line of sight was parallel to the floor. They were next handed a game controller and shown a virtual, yellow "X" that was translationally controlled by the head tracker (Figure 2c, which shows a typical degree of translational error). The initial position of the X represented the location where the real-world crosshair should be located according to the tracker. The observers then used the game controller to adjust the position of the X until it was aligned with both the real and virtual crosshairs (Figure 2d). This adjustment added a translational offset to the values reported by the head tracker, which translationally corrected for the way the HMD was

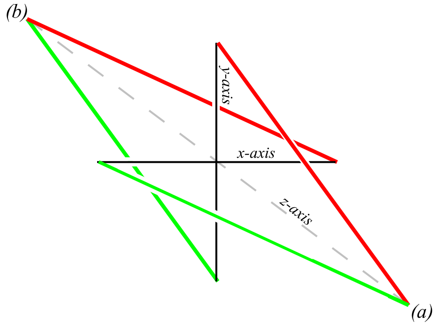

Figure 3: *Side view of the 3D Compass. Observers looked along the z-axis, from point (a) to point (b). See color plate.*

sitting on their head.

Rotational Tracker Error: The goal of the third calibration step was to correct for rotational tracker errors around the observers' pitch (up/down) and yaw (side/side) axis. The tracker also had roll (twist) errors, but these errors were not important for this task. The observers were shown the same real and virtual crosshairs as in the previous step and asked to perform the same boresighting task (Figure 2b). This time the observers were shown a 3-dimensional crosshair that we called the 3D Compass (see Figure 3). The 3D Compass is rotationally controlled by the head tracker, but it is translationally centered at the virtual crosshair. The shape of the 3D Compass is such that if there is any rotational offset when aligned with the real world crosshair, its 2D projection results in an accidental view with a star-like shape (Figure 2e, which shows a typical degree of rotational error). However, when all rotational errors have been compensated, the 2D projection results in another accidental view that looks like a plus sign (Figure 2f). The observers were given a game controller and asked to adjust the shape until it became a plus. This adjustment added a pitch and yaw offset to the values reported by the head tracker. The 3D Compass is sensitive and easy to use; we believe it is a novel contribution to AR calibration techniques.

Together, these calibration procedures resulted in accurate registration between the virtual and real worlds. Observers were required to perform this calibration before every block of trials in the AR and VR viewing conditions. Also, if the observers touched, moved, or otherwise jostled the HMD at any point during the trials, the calibration procedure was repeated before any further data was collected.

5 Results

We analyzed *judged distance* results from $N = 768$ data points. A histogram revealed a normal distribution with two outlying values, which were likely data entry errors. These were replaced with the mean of the remaining values in the experimental cell [Barnett and Lewis 1994]. As is typical with distance perception, we found that variability increased with increasing distance (e.g., observers were following Weber's law [Sekuler and Blake 2001]; see Figures 4 and 6). Because of this, the judged distance results do not meet the homogeneity of variance requirement for ANOVA analysis. However, an examination of the *normalized error* results with a histogram showed a normal distribution with homogeneous variability over all independent variables, including distance. Because of this, and because it is normalized with respect to distance, and because it increased experimental power, for normalized error we analyzed all $N = 1024$ data points (both the experimental and the noise trials). All ANOVA analysis was conducted with normalized error.

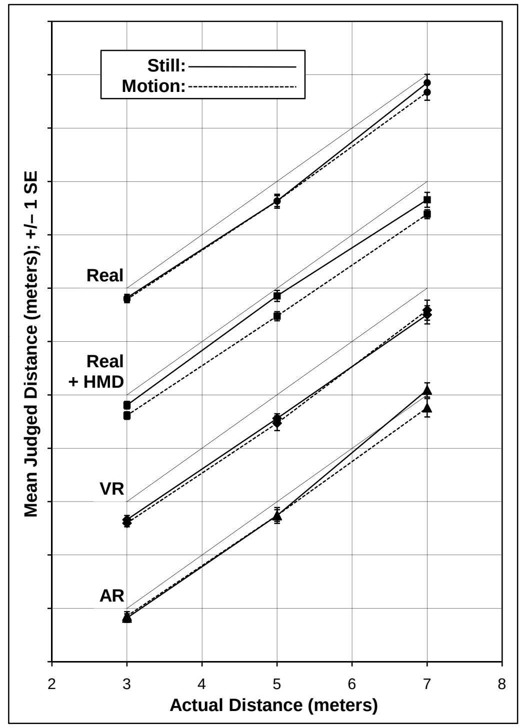

Figure 4: *Depth judgments over all observers* $(N = 768)$. *The diagonal lines are veridical; the results are offset by viewing condition for clarity. For this and subsequent graphs, absent error bars indicate an error interval that is smaller than the mean symbol.*

Figure 4 shows the main results as judged distance versus actual distance; for clarity these are offset and grouped by environment. In the Real condition, observers underestimated the distance slightly (*normalized error* = 94.1%; $N = 1024$), but their performance did not interact with either parallax or distance. Observers performed similarly in the AR condition (96.0%). In the VR condition, observers showed an underestimation effect (91.1%), which is significantly different than 100% $(F(1, 15) = 13.10, p = .003, N = 256)$ but is small by historical standards (see Figure 7). The difference between the AR and VR environments was also significant $(F(1, 15) = 5.86, p = .029, N = 512)$.

The only effect of motion parallax occurred for the Real+HMD environment, which showed a significant difference between the Still (94.6%) and Motion (89.6%) conditions $(F(1, 15) = 5.29, p = .036, N = 256)$. This effect is somewhat consistent with Willemsen et al. [2004], who found that the mass and inertia of an HMD caused depth underestimation. In this case, we could expect that the Motion condition would make HMD mass and inertia effects more pronounced.

Figure 5 shows the normalized error per observer. Note that observers 1, 6, and 13 underestimated to a much greater degree than the rest of the observers. This suggests splitting the observers into two groups, an underestimating group consisting of observers 1, 6, and 13, and a group with the remaining observers. Of the 1024 normalized error observations, a discriminate analysis with this model correctly places 77.0% of the observations into the proper group, and a regression on this model accounts for $r^2 = 23.2\%$ of the observed variance.

Figure 6 shows the results for the remaining 13 observers when these 3 underestimating observers are removed. Here the same results as above are observed, but the degree of underestimation is considerably reduced. Observers performed veridically in both the

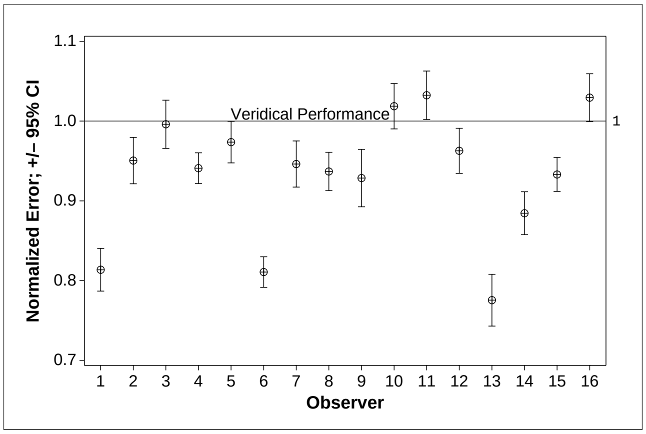

Figure 5: *The normalized error per observer* $(N = 1024)$. *Note the underestimation of observers 1, 6, and 13.*

Real (97.9%; $N = 832$ including noise trials) and AR (98.9%) environments. Observers underestimated in the VR environment (94.1%), which is still significantly different than 100% although the sample size is smaller $(F(1, 12) = 6.79, p = .023, N = 208)$. There is trend of significance between the AR and VR environments $(F(1, 12) = 4.08, p = .066, N = 416)$, which becomes significant if we exclude the noise trials $(F(1, 12) = 6.32, p = .027, N = 312)$. And for the Real+HMD environment, a significant difference remains between the Still (97.8%) and Motion (91.5%) conditions $(F(1, 12) = 5.92, p = .032, N = 208)$.

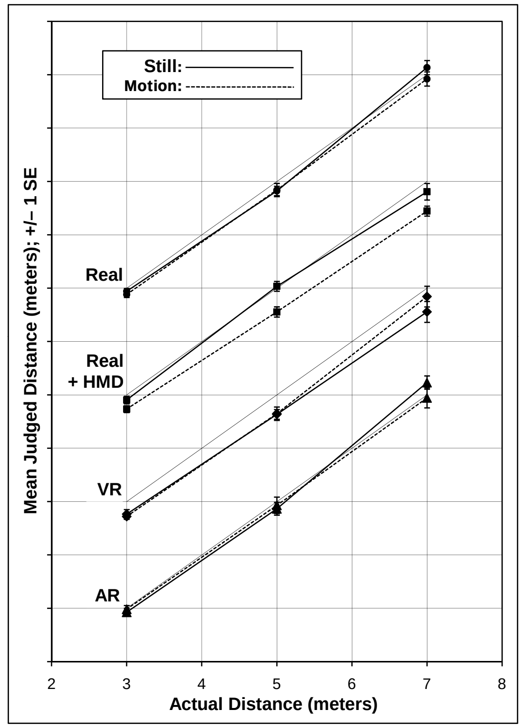

Figure 6: *Depth judgments with underestimating observers removed* $(N = 624)$*; see Figure 5.*

6 Discussion and Conclusions

Table 2 and Figure 7 show the normalized error from a number of recent egocentric depth perception experiments that investigated AR, VR, real-world environments, and real-world environments seen through an HMD. There are several interesting findings in this table and graph. First, the overall trend of egocentric depth underestimation in VR environments, relative to other environments, is clear. Second, Figure 7 provides a context for the magnitude of the underestimation observed in the current study. The amount of underestimation for the Real condition agrees well with previous studies. The amount of underestimation for the VR environment is low compared to most previous studies, and the amount of underestimation for the AR environment is also low compared to the small number of previous studies. A likely reason for the relatively small amount of observed VR underestimation is the ability of the nVis nVisor display to be calibrated in AR mode, and then used in VR mode. Because the real world is visible in AR, critical scene parameters, such as field of view and position and orientation tracker corrections, can be set relative to real-world, ground truth referent objects. This degree of calibration accuracy is not possible in pure VR displays.

We expected motion parallax to make depth judgments more accurate, because motion parallax adds to the depth cues that are available in the scene. Contrary to our expectations, motion parallax did not make depth judgments more accurate; its only effect was an interaction with environment—it made depth judgments less accurate (more underestimated) in the Real+HMD environment. This can be compared to the findings of Williamsen et al. [2004], who found underestimation in a Real+HMD environment compared to a Real environment when viewing objects without motion parallax. However, we only found underestimation in the Real+HMD environment in the motion parallax condition; we found no parallax effects in the VR or AR environments, where observers were also wearing the HMD. And, although Beall et al. [1995] found that motion parallax has a very week effect on an observer's perception of depth, we found a significant motion parallax effect in the Real+HMD environment.

Our most interesting experimental result was the lack of underestimation in AR compared with VR. To the best of our knowledge, this is the first experiment to directly compare egocentric depth perception in AR and VR using the same experimental framework. A number of hypothesized reasons for the VR underestimation effect have been studied [Swan II et al. 2007]; these include the HMD's limited field of view, the weight and inertia of the HMD, monocular versus stereo viewing, the quality of the rendered graphics, knowledge that the virtual scene represents an actual real-world location, and the effect of practice with feedback. To date, although some of these reasons have been found to contribute to VR underestimation, none of them fully describe it. In this experiment we have added to this body of knowledge by demonstrating that the effect disappears when observers view virtual objects against an actual, real-world scene. We have also demonstrated that observers can make accurate egocentric depth judgments in AR, when measured using the same directed walking techniques that have been widely studied in VR.

Acknowledgments

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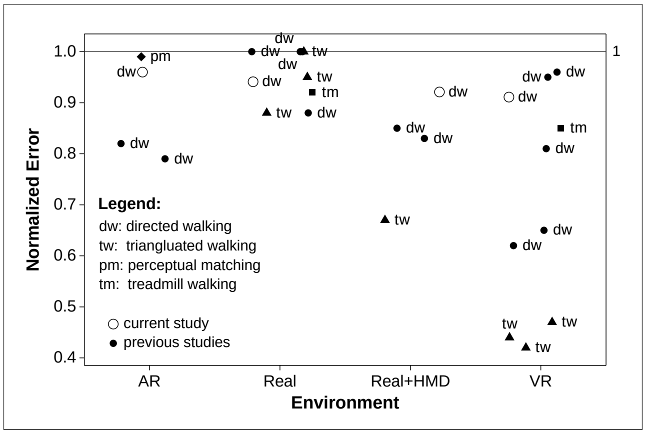

Figure 7: *The normalized egocentric depth perception error from the current study* $(N = 1024)$*, in the context of many reported studies. This graph visualizes the information in Table 2.*

Table 2: *Normalized Error (NE) results from a variety of recent studies, with distances in meters. This information is visually depicted in Figure 7.*

Study	Distances	NE	Protocol
Augmented Reality			
Current Study	3.0 – 7.0	96%	Direct Walking
[Swan II et al. 2006]	5.25 – 44.31	99%	Perceptual Matching
[Swan II et al. 2007] (AR)	3.0 – 7.0	79%	Direct Walking
[Swan II et al. 2007] (AR+Real)	3.0 – 7.0	82%	Direct Walking
Real World			
Current Study	3.0 – 7.0	94%	Direct Walking
[Interrante et al. 2006]	3.0 – 9.2	100%	Direct Walking
[Knapp 1999]	5.0 – 15.0	100%	Triangulated Walking
[Swan II et al. 2007]	3.0 – 7.0	88%	Direct Walking
[Thompson et al. 2004]	5.0 – 15.0	95%	Triangulated Walking
[Willemsen and Gooch 2002]	2.0 – 5.0	100%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	100%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	88%	Triangulated Walking
[Witmer and Sadowski 1998]	4.6 – 32.0	92%	Treadmill Walking
Real World seen through HMD			
Current Study	3.0 – 7.0	92%	Direct Walking
[Swan II et al. 2007]	3.0 – 7.0	83%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	85%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	67%	Triangulated Walking
Virtual Reality			
Current Study	3.0 – 7.0	90%	Direct Walking
[Interrante et al. 2006] (Base)	3.0 – 9.2	95%	Direct Walking
[Interrante et al. 2006] (Post)	3.0 – 9.2	96%	Direct Walking
[Durgin et al. 2002]	2.0 – 8.0	65%	Direct Walking
[Knapp 1999]	5.0 – 15.0	42%	Triangulated Walking
[Thompson et al. 2004]	5.0 – 15.0	44%	Triangulated Walking
[Willemsen and Gooch 2002]	2.0 – 5.0	81%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	62%	Direct Walking
[Willemsen et al. 2004]	4.0 – 8.0	47%	Triangulated Walking
[Witmer and Sadowski 1998]	4.6 – 32.0	85%	Treadmill Walking

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